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Joseph Hamill, *University of Massachusetts - Amherst*

Bryan C. Heiderscheit

Christine D. Pollard

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Gender Differences in Lower Extremity Coupling Variability During an Unanticipated Cutting Maneuver

Christine D. Pollard^{1}, Bryan C. Heiderscheit²,
Richard E.A. van Emmerik¹, and Joseph Hamill¹*

¹Univ. of Massachusetts; ²Univ. of Wisconsin Medical School

The purpose of this study was to determine if gender differences exist in the variability of various lower extremity (LE) segment and joint couplings during an unanticipated cutting maneuver. 3-D kinematics were collected on 24 college soccer players (12 M, 12 F) while each performed the cutting maneuver. The following intralimb couplings were studied: thigh rotation (rot)/leg rot; thigh abduction-adduction/leg abd-add; hip abd-add/knee rot; hip rot/knee abd-add; knee flexion-extension/knee rot; knee flx-ext/hip rot. A vector-coding technique applied to angle-angle plots was used to quantify the coordination of each coupling. The average between-trial standard deviation of the coordination pattern during the initial 40% of stance was used to indicate the coordination variability. One-tailed *t*-tests were used to determine differences between genders in coordination variability for each coupling. Women had decreased variability in four couplings: 32% less thigh rot/leg rot variability; 40% less thigh abd-add/leg abd-add variability; 46% less knee flx-ext/knee rot variability; and 44% less knee flx-ext/hip rot variability. These gender differences in LE coordination variability may be associated with the increased incidence of ACL injury in women. If women exhibit less flexible coordination patterns during competition, they may be less able to adapt to the environmental perturbations experienced during sports. These perturbations applied to a less flexible system may result in ligament injury.

Key Words: ACL, knee injury, kinematics, joint coordination

Female participation in both college and recreational sports has been growing steadily each year. Coincident with this increase in participation is an increased occurrence of certain injuries that are more frequent in this population of women.

¹Dept. of Exercise Science, Univ. of Massachusetts, Amherst, MA 01003; ²Dept. of Orthopedics and Rehabilitation, Univ. of Wisconsin Medical School, Madison, WI 53706.
*C.D. Pollard is now with the Dept. of Biokinesiology and Physical Therapy, USC, 1540 E. Alcazar, CHP-155, Los Angeles, CA 90089-9006.

Female athletes who participate in jumping and cutting sports reportedly are 4 to 6 times more likely to sustain a serious knee injury than male athletes participating in the same sports (Griffin, Agel, Albohm, et al., 2000; Hutchinson & Ireland, 1995; Ireland, 1999). More specifically, women have a noncontact anterior cruciate ligament (ACL) injury rate 4 times greater than that of their male counterparts (Arendt & Dick, 1995). Understanding the mechanisms for this disproportionate incidence of injury between genders has become a primary concern.

Because it is understood that noncontact ACL injuries most often occur during some form of cutting or landing task, biomechanical studies have examined gender differences in lower extremity kinematics while performing such tasks. These studies have primarily focused on peak knee joint angles with the aim of identifying any kinematic patterns that may result in increased loading of the ACL in women.

During the deceleration phase of landing, a reduction in peak knee flexion angle has been frequently observed among women relative to men (Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Lephart, Ferris, Riemann, Myers, & Fu, 2002). In addition, increases in nonsagittal plane motion such as hip adduction, hip internal rotation, and knee abduction are present among females during landing and running (Ferber, Davis, & Williams, 2003; Ford, Myer, & Hewett, 2003). Furthermore, women demonstrate increases in knee abduction during cutting (Malinzak, Colby, Kirkendal, Yu, & Garrett, 2001; McLean, Neal, Myers, & Walters, 1999). The combination of these motions is reflective of the *in vitro* pattern that places the greatest load on the ACL, which is an internal rotation tibial torque and valgus moment placed on the knee flexed between 0–40° (Markolf, Burchfield, Shapiro, et al., 1995).

Although research on gender differences in lower extremity kinematics such as peak angular motion is informative, the coordination of lower extremity joint and segment motions may also be of interest. A number of studies have investigated lower extremity coordination in running as related to injury (Hamill, Bates, & Holt, 1992; Hamill, van Emmerik, Heiderscheit, & Li, 1999; McClay & Manal, 1997). For example, Hamill et al. (1992) reported that a disruption in timing between the subtalar joint and knee joint might be a mechanism for knee injury during running. With respect to gender differences during a task such as drop landing, Decker, Torry, Wyland, Sterett, and Steadman (2003) reported that females demonstrate a more erect lower extremity posture and suggest that this could be harmful. These changes in discrete angles at multiple joints indicate the need for a joint coordination measure that can capture the between-joint interaction.

Studies that have looked at joint coordination have suggested that coordination variability offers flexibility in adapting to perturbations and is essential to the changing coordination patterns during locomotion (Hamill et al., 1999; van Emmerik & van Wegen, 2000). Reduction in coordination variability has been observed among individuals with patellofemoral pain compared to asymptomatic individuals (Hamill et al., 1999; Heiderscheit, Hamill, & van Emmerik, 2002). Hamill et al. (1999) suggested that while the lack of coordination pattern variation could indicate an injury state, it could also result in constant stress on cartilage, tendon, and ligaments that could ultimately cause degenerative changes. If women display reduced coordination pattern variability during a task such as an unanticipated cutting maneuver, their ability to adapt to the inherent environmental perturbations experienced during cutting maneuvers in sports may be limited, thus increasing the risk for injury such as an ACL tear.

The purpose of this study was to determine if gender differences exist in the variability of various lower extremity segment and joint couplings during an unanticipated cutting maneuver. It was hypothesized that women would demonstrate reduced variability in these intralimb couplings across the initial 40% of the stance phase of an unanticipated cutting maneuver as compared to men. The initial 40% of stance was selected, as two critical events were observed to occur during this phase: 0–40° of knee flexion and deceleration of the cutting maneuver (Pollard, Davis, & Hamill, 2004).

Methods

Using data from the literature (Heiderscheit et al., 2002), we estimated ample size for a minimal statistical power of 80% ($p = 0.05$). All sample size and power calculations were completed using G*Power Software (Erdfelder, Faul, & Buchner, 1996). Given the variation of the dependent measures included in this study, 12 participants per group were deemed adequate.

Participants consisted of 12 female (age 19.3 ± 1.1 yrs; height 1.66 ± 0.05 m; mass 62.5 ± 6.9 kg) and 12 male (age 19.7 ± 1.5 yrs; height 1.80 ± 0.07 m; mass 76.1 ± 5.9 kg) college soccer players. All had at least 12 years of experience in their sport (women, 12.3 ± 2.2 yrs; men, 13.7 ± 1.8 yrs). All participants were in season during data collection. Approval for their participation in this study was obtained from the University of Massachusetts Institutional Review Board. The participants had no history of significant lower extremity injury and were injury free at the time of data collection (determined by verbal questioning from a licensed physical therapist).

The participants performed three tasks: a 45° cutting maneuver, a straight-ahead run, and a jump stop. The run and jump-stop tasks were included to present the participant with three options (cut, run, jump stop) in order to decrease anticipation of the cutting task. An illuminated target board triggered by a photocell located 1.5 m from the force platform was used to signal for the appropriate task. The participant was instructed that a yellow light would indicate a 45° cut, a green light would indicate a straight-ahead run, and a red light would indicate a jump stop. Each individual completed a practice session that included several preplanned and several unanticipated trials of each of the three tasks. Seven trials of each task were randomly performed with all testing completed in one session. Each participant was given approximately 60–90 s of rest between trials so as to reduce the potential effects of fatigue.

Following the practice trials, four retroreflective tracking markers attached to a polypropylene shell were securely placed on the lateral surface of the participant's right thigh, leg, and heel counter of shoe. Three additional tracking markers were placed on the right anterior superior iliac spine, right iliac crest, and L₅/S₁ joint line to define the right hemi-pelvis. Calibration markers were placed on bilateral greater trochanters, right medial and lateral femoral epicondyles, right medial and lateral malleoli, and right first and fifth metatarsal heads to locate the segment origins. Once the markers were placed, a standing calibration trial was recorded to establish anatomical neutral. The calibration markers were removed after the standing trial, while the tracking markers remained on the participant throughout the data collection session. The same individual placed the markers for all participants. The participants all wore spandex shorts and court shoes during data collection.

Kinematic data were collected using a Qualisys, seven-camera, 3-D motion analysis system (Qualisys, Gothenburg, Sweden) at a sampling frequency of 240 Hz. The cameras were interfaced to a personal computer and encircled a force platform embedded within the floor (Advanced Mechanical Technologies, Newton, MA). The force platform was interfaced to the same personal computer and sampled (1920 Hz) via a 12-bit analog-to-digital converter (ComputerBoards, Watertown, MA), thereby providing synchronized data collection. The force platform was only used to identify the stance phase of the cutting maneuver and to identify the footstrike region for the various tasks.

Running speeds of cutting motion on approach to and exiting the force platform were monitored with four photocells located along the runway. To measure approach speed, we aligned two photocells parallel to the approach runway with one photocell located 3 m prior to the force platform and the other located 1 m prior. To measure exit velocity, we aligned two photocells parallel to the exit pathway with one photocell located 1 m from the force platform and the other 3 m away. For all trials, it was required that approach speed fall between 5.5 and 6.5 m/s and exit speed fall between 4.5 and 5.5 m/s. The area on the runway to the left of the force platform was lined with tape to designate the path at which the participant had to proceed (45°) (Figure 1). In addition, six cones were placed (3 on each side) to create a pathway the participant had to remain within to perform a successful cut.

A cutting trial was deemed successful if: (a) the right foot came in contact with the force platform; (b) the initial left foot contact following the cutting action was near the designated 45° angle line; (c) the participant remained within the pathway designated by the cones; and (d) the required approach and exit speed were maintained. A straight-ahead trial was deemed successful if the right foot came into contact with the force platform and the participant continued along the straight-ahead path. A jump stop was deemed successful if the right foot came into contact with the force plate and the participant proceeded forward to land with both feet just after the force platform.

Q-Trac software (Qualisys, Inc.) was used to digitize the kinematic data corresponding to the right stance phase (foot-ground contact on the force platform) for each trial of the 45° cutting task. The data from the straight-ahead running and jump-stop trials were not analyzed. A nonlinear transformation technique was used to transform the 2-D coordinates from the seven cameras to 3-D coordinates. The local coordinate systems of the right thigh, leg, and foot were derived from the standing calibration trial. Coordinate data were low-pass filtered using a fourth-order Butterworth filter with an 8-Hz cutoff frequency. Using Visual 3D™ software (C-Motion, Rockville, MD), we calculated 3-D joint angles for the hip and knee and segment angles for the thigh and leg for each trial. The angle data were linearly interpolated to 101 data points, with each point representing 1% of the stance phase (0–100%).

Based on the ACL loading patterns identified in the *in vitro* literature, the following intralimb couplings from the right lower extremity were examined: thigh rotation/ leg rotation; thigh abduction-adduction/ leg abduction-adduction; hip abduction-adduction/ knee rotation; hip rotation/ knee abduction-adduction; knee flexion-extension/ knee rotation; and knee flexion-extension/ hip rotation. Angle-angle plots were created for each coupling with the proximal segment comprising the abscissa and the distal comprising the ordinate. Consistent with Heiderscheit et al. (2002), we quantified joint coordination using a modification of the vector

Figure 1 — Runway, cutting, and camera setup (pc = photocell). The target board consisted of a green, yellow, and red LED to signal the participants to the task to be performed (e.g., running straight ahead, cutting at 45°, jump stop).

coding technique suggested by Sparrow, Donovan, van Emmerik, and Barry (1987). Coupling angles were calculated using the orientation of the resultant vector to the right horizontal between two adjacent data points in the stance phase. Following conversion from radians to degrees, the resulting range of values for coupling angles was between 0–90°. The standard deviation of the coupling angles across trials was calculated for each percent of stance, providing a measure of between-trial, within-subject variability. This procedure was repeated for each intralimb coupling.

The variability was averaged across the initial 40% of the stance phase, as this corresponds to the initial loading/deceleration phase of the cutting maneuver and includes the region of stance where the initial 40° of knee flexion occurs. The average variability across the initial 40% of the stance phase was compared between genders using a one-tailed *t*-test ($\alpha = 0.05$). This was repeated for each coupling.

To further evaluate the results, we calculated effect sizes (ES) to express differences between genders relative to the pooled standard deviation. Small (0.2), moderate (0.5), and large (0.8) effect sizes were defined according to Cohen (1990). Together, the effect sizes and *p*-values were evaluated as the basis for discussing gender differences.

Table 1 Mean Coordination Variability From 0 to 40% of Stance Phase for Each Coupling

Lower extremity couplings	Women	Men	Diff.	Effect size	<i>p</i> -value
Thigh rotation/ Leg rotation	16.5° ±4.9	24.3° ±11.6	-7.8°	0.87	0.04
Thigh abduction-adduction/ Leg abduction-adduction	9.7° ±2.9	16.2° ±7.2	-6.5°	1.18	0.01
Hip abduction-adduction/ Knee rotation	18.3° ±8.2	20.7° ±8.5	-2.4°	0.29	0.54
Hip rotation/ Knee abduction-adduction	25.6° ±3.9	24.1° ±9.5	1.5°	0.20	0.97
Knee flexion-extension/ Knee rotation	6.6° ±2.9	12.4° ±9.6	-5.8°	0.81	0.05
Knee flexion-extension/ Hip rotation	7.7° ±3.4	13.9° ±9.8	-6.2°	0.84	0.05

Results

It was hypothesized that women would demonstrate less intralimb coordination variability than men. During the initial 40% of the stance phase, they demonstrated significantly less variability in four of the six couplings examined as compared to their male counterparts (Table 1). Women demonstrated 32% less thigh rotation/ leg rotation variability, $p = 0.04$; 40% less thigh abduction-adduction/ leg abduction-adduction variability, $p = 0.01$; 46% less knee flexion-extension/ knee rotation variability, $p = 0.05$; and 44% less knee flexion-extension/ hip rotation variability, $p = 0.05$. Figure 2 presents the mean coordination variability of all six couplings across the stance phase.

Although the remaining couplings did not display gender differences during the initial 40% of stance, there was a trend toward decreased variability in the women. For example, they all demonstrated 12% less hip abduction-adduction/ knee rotation variability during the first 40% of stance. Following visual inspection of the data, we performed a post hoc analysis on the hip rotation/ knee abduction-adduction coupling during 35–45% of stance. Women were observed to demonstrate 51% less coordination variability than men during this stance region.

Discussion

The purpose of this study was to determine if gender differences exist in the variability of specific lower extremity segment and joint couplings during an unanticipated cutting maneuver. It was hypothesized that women would demonstrate reduced coordination variability. Based on the results of this study, our hypothesis was supported, as women displayed less coordination variability in four of the six couplings examined.

Figure 2 — Mean coordination variability of six couplings across the stance phase of an unanticipated cutting maneuver (women: thick line; men: thin line).

As was suggested by Hamill et al. (1999), decreased variability present in intralimb couplings may be related to less flexible coordination patterns. In turn, the lack of pattern flexibility or adaptability may increase the risk for injury. Because it is known that women incur noncontact ACL injury more often than men, the question arises as to whether they exhibit less flexible patterns of coordination which may limit their ability to adapt to the necessary environmental perturbations frequently experienced in sports. The data from the current study indicate that women do indeed display a reduction in coordination variability during an unanticipated cutting maneuver.

In the current study of college soccer players, female participants demonstrated decreased variability in several lower extremity segment and joint couplings as compared to male participants during an unanticipated cutting maneuver. These various couplings are considered important based on the ACL loading patterns identified in the *in vitro* literature. *In vitro* research has demonstrated that an internal rotation tibial torque and valgus (abduction) moment placed on the knee flexed 0–40° will impose the greatest load on the ACL (Markolf et al., 1995). In addition, recent *in vitro* work by Fung and Zhang (2003) demonstrated an increased risk of ACL impingement with tibial external rotation and abduction. While it remains unclear from the *in vitro* literature which is more deleterious—whether it is tibial internal rotation causing increased ACL strain, or tibial external rotation causing increased risk of ACL impingement—it is clear that transverse and frontal plane motion affect the ACL. Of the couplings demonstrating significant reduction in variability among women, all involved either a transverse or frontal plane component of motion.

Previous analysis of the same sample of participants demonstrated no gender differences in peak knee or hip joint rotation angles as well as flexion angles (Pollard et al., 2004). However, the current study revealed decreased variability in both the knee flexion-extension/ knee rotation coupling and the knee flexion-extension/ hip rotation coupling. The lack of discrete angle gender differences in the presence of coordination variability differences suggests that joint coordination or interaction may be a key biomechanical parameter for future study.

Gender differences in variability of lower extremity coordination during the initial loading phase of an unanticipated cutting maneuver may underlie the disproportionate incidence of noncontact ACL injury in women. If in fact they are exhibiting less flexible coordination patterns during high-level competition as compared to men, women may have decreased ability to adapt to the frequent external perturbations incurred during play. These external perturbations applied to a less flexible system may result in acute injury or may lead to repetitive microtrauma to the ligament, resulting in a predisposition to noncontact ACL injury.

Although this study focused on healthy individuals, the variability reduction in the thigh rotation/ leg rotation coupling in women was similar to that reported by Hamill et al. (1999) and Heiderscheit et al. (2002) when comparing individuals with patellofemoral pain to those without. The findings of this study combined with the findings of Hamill et al. and Heiderscheit et al. suggest that decreased joint coordination may play a role in lower extremity injury. More specifically, decreased joint coordination may be contributing to the increased incidence of certain injuries in women as compared to men. Aside from ACL injury, these include patellofemoral pain syndrome and tibial stress fractures.

While the results of this study clearly demonstrate gender differences in lower extremity coupling variability during the unanticipated cutting maneuver, the absolute values observed with the coupling variability may be different in a field setting. The additional sources of perturbations, and therefore increased complexity in task organization, may alter the variability present in lower extremity couplings. Although the experimental design employed in this study presented the participants with an external perturbation (visual task trigger), it was conducted in a laboratory setting in which many environmental conditions were controlled.

In summary, a reduction in coordination variability was observed among various lower extremity couplings in women during an unanticipated cutting task.

Further research is needed to compare gender differences in the variability of lower extremity segment and joint couplings in different sample populations during lower extremity tasks such as cutting, jump stopping, or landing. A better understanding of these differences may offer insight into the effects of training and experience on lower extremity coordination. Although there are clear gender differences in coordination variability, the relationship between reduced variability and increased injury risk cannot be deduced from the current study design. Therefore, a longitudinal design examining the incidence of injury among persons displaying a reduction in coordination variability is warranted.

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